Upgrade of SRS Electronics for PRad GEMs readout

Kondo Gnanvo

University of Virginia, Charlottesville, VA

On behalf of the PRad Collaboration

Outline

- ✓ The PRad Experiment
- ✓ SRS Readout for PRad GEM trackers
- ✓ SRS Firmware Upgrade
- ✓ Integration to JLab DAQ system (CODA)

UNIVERSITY of VIRGINIA

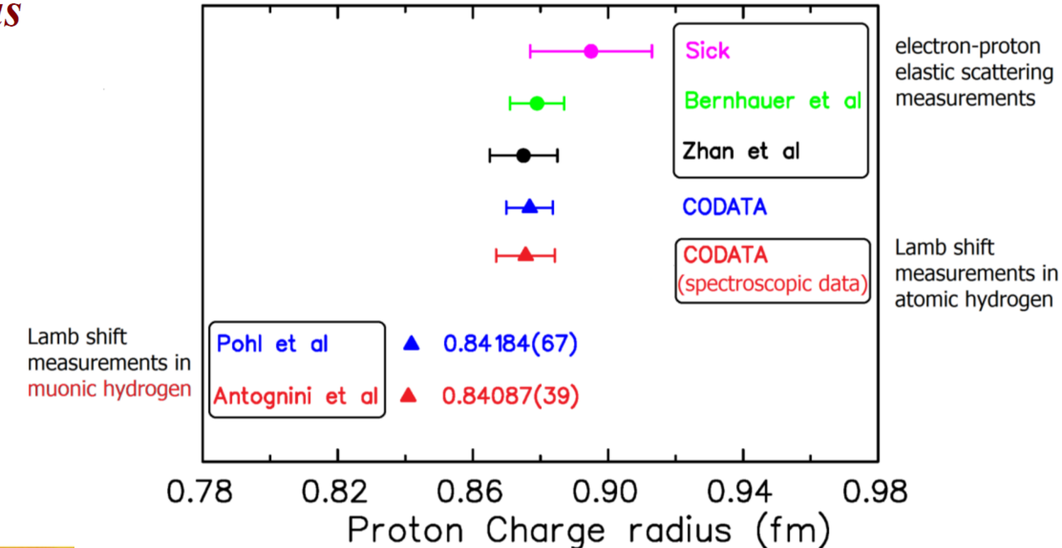
The Proton Charge Radius Puzzle

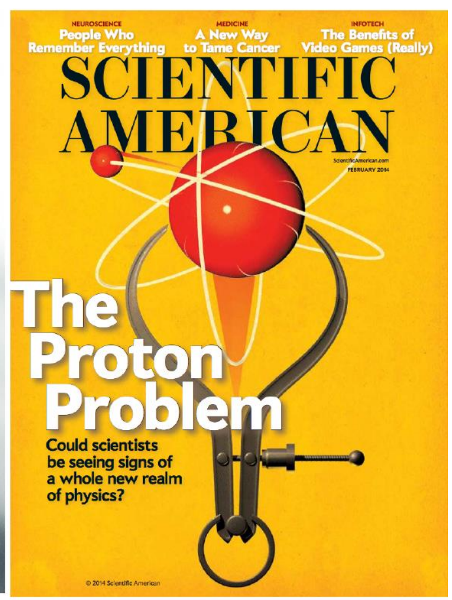
Methods for measuring proton charge radius

- Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)

$$\sqrt{<r^2>} = \sqrt{-6\frac{dF(\vec{q})}{dq^2})|_{q^2=0}}$$

- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift





- **7σ** discrepancy between the atomic hydrogen Lamb shift and muonic hydrogen Lamb shift
- New Experiments:
  - Atomic spectroscopy
  - Muon spectroscopy (PSI)
  - Muon – proton scattering (MUSE, PSI)
  - Electron - Proton scattering with different schematics (JLab, Mainz)

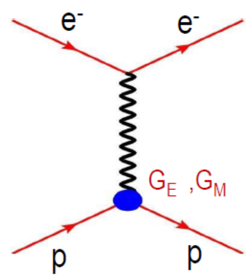
The PRad Experiment @ JLab: ep → ep Scattering

The Proton Charge Radius from $ep \to ep$ Scattering Experiments

- In the limit of first Born approximation the elastic *ep* scattering (one photon exchange):

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

$$Q^2 = 4EE'\sin^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$



- Structure less proton:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2\left[1 - \beta^2 \sin^2\frac{\theta}{2}\right]}{4k^2 \sin^4\frac{\theta}{2}}$$

- G_E and G_M were extracted using Rosenbluth separation (or at extremely low Q^2 the G_M can be ignored, like in the PRad experiment)
- The Taylor expansion at low Q^2:

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2\rangle + \frac{Q^4}{120}\langle r^4\rangle + \ldots$$

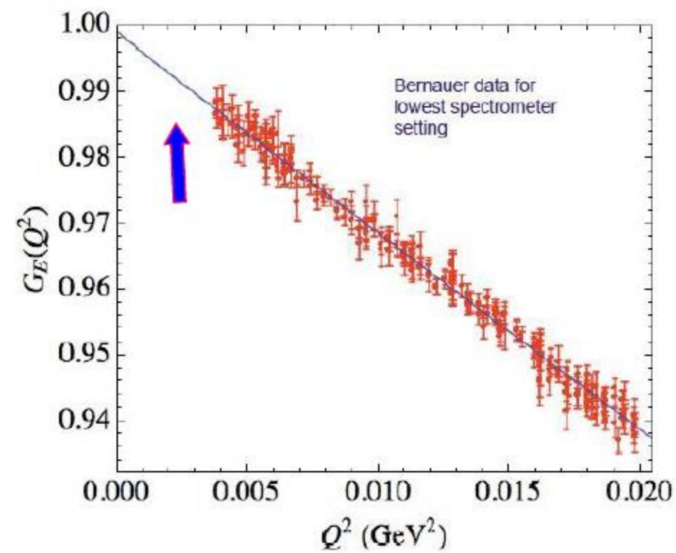
- Definition of the Proton Radius: (r.m.s. charge radius given by the slope)

$$\langle r^2\rangle = -6 \left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$$

A. Gasparian CLAS col. meeting, 2015

PRad Experiment (E12-11-106):

- **High "A" rating (JLab PAC 39, June 2011)**
- Experimental goals:
  - Very low Q^2 (2×10^{-4} to 4×10^{-2})
  - 10 times lower than current data @ Mainz
  - Sub-percent precision in $\langle r_p^2\rangle$ extraction



Mainz low Q^2 data set

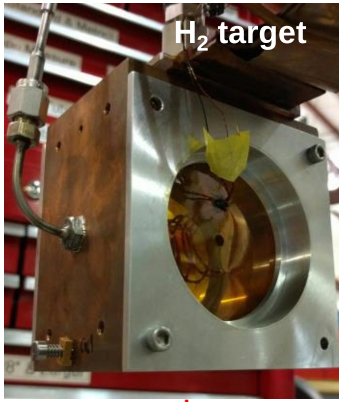
Specifications for PRad Experiment

- Non Magnetic spectrometer
- High resolution and high acceptance calorimeter ⇨ low scattering angle [0.7° - 3.8°]
- Simultaneous detection of ee → ee (Moller Scattering) ⇨ minimize systematics
- High density windowless H_2 gas target ⇨ minimze background
- clean CEBAF electron beam (1.1 GeV and 2.2 GeV) ⇨ minimze background

The PRad Experimental Setup in Hall B

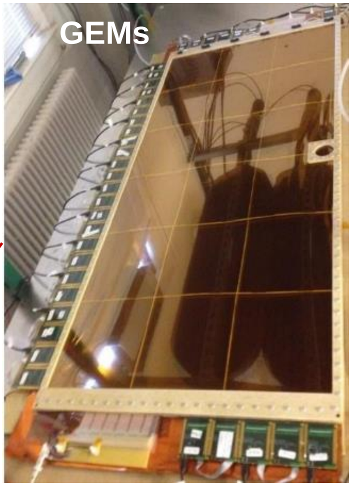
Target specs:

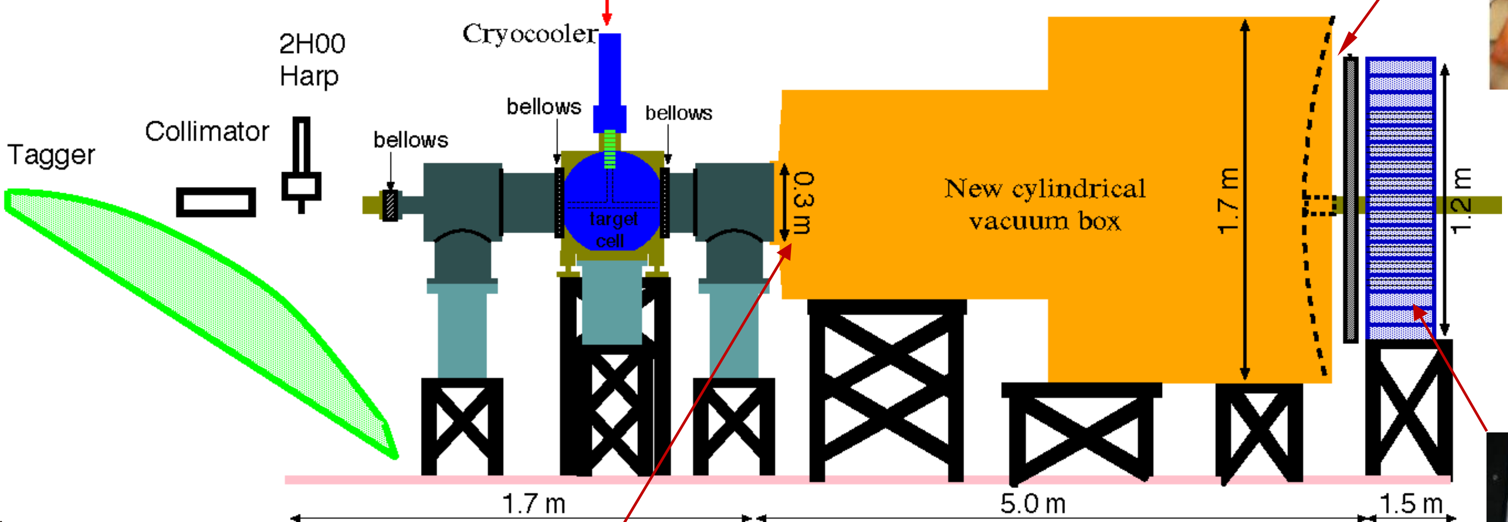
- *cell length 4.0 cm*
- *cell diameter 8.0 mm*
- *cell material 30 μm Kapton*
- *input gas temp. 25 K*
- *target thickness 1×10^{18} H/cm^2*
- *average density 2.5×10^{17} H/cm^3*
- *Cell pressure 0.6 torr*
- *Vacuum in target chamber ~5×10^{-3} torr*



GEMs:

- *factor of >10 improvements in coordinate resolutions*
- *similar improvements in Q2 resolution (very important)*
- *unbiased coordinate reconstruction (including transition region)*
- *increase Q2 range by including Pb-glass part*





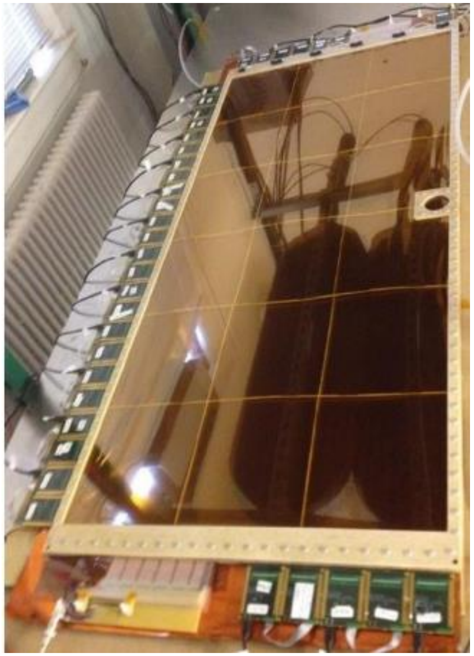
HyCal specs:

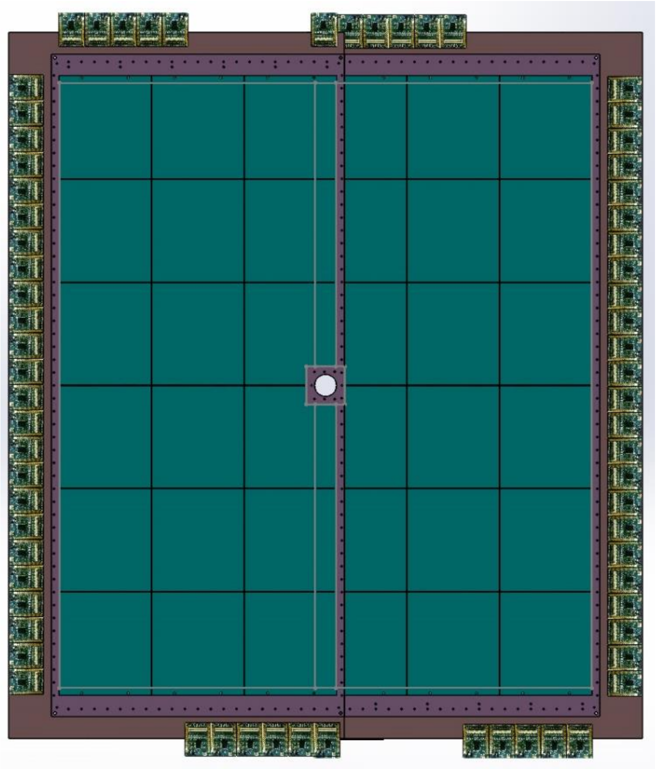
- *34 x 34 matrix of 2.05 x 2.05 x 18 cm^3 PbWO4 shower detectors*
- *576 Pb-glass shower detectors (3.82x3.82x45.0 cm^3)*
- *5.5 m from H_2 target (~0.5 sr acceptance)*
- *Resolutions for PbWO4 shower: $\sigma/E = 2.6\%/\sqrt{E}$, $\sigma_{xy} = 2.5\ mm/\sqrt{E}$*
- *Resolution for Pb-glass shower detectors factor of ~2.5 worse*

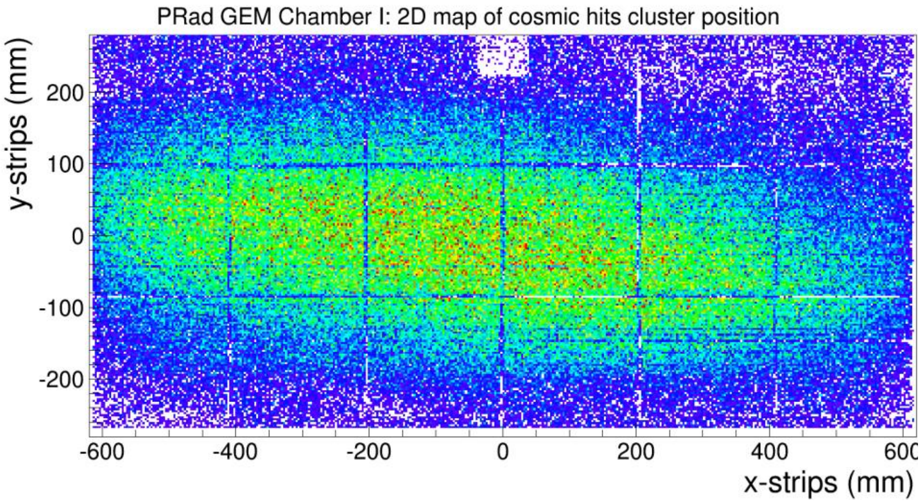
PRad GEMs

- Two large GEM chambers right in front of HyCal covering an area of ~ 120 cm x 110cm.
- Each chamber is a COMPASS triple-GEM (120 cm x 54 cm) wit 2D strips readout.
- SRS Readout Electronics:
  - 36 APV cards per Chamber
  - 4608 Readout Channels per Chamber

PRad GEM chamber



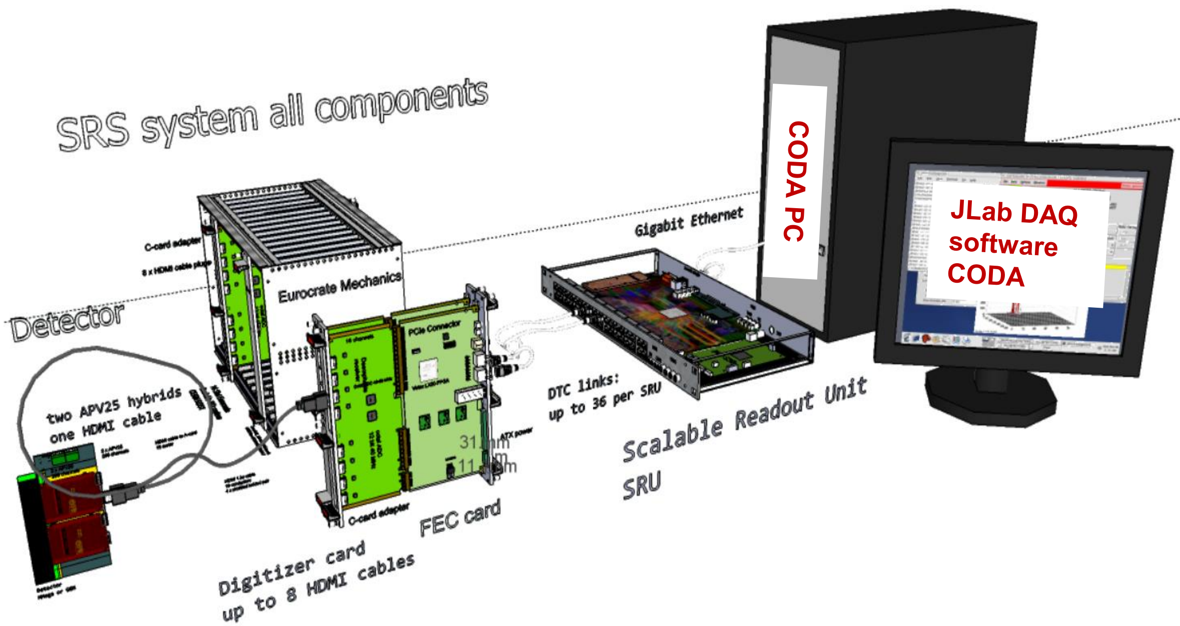


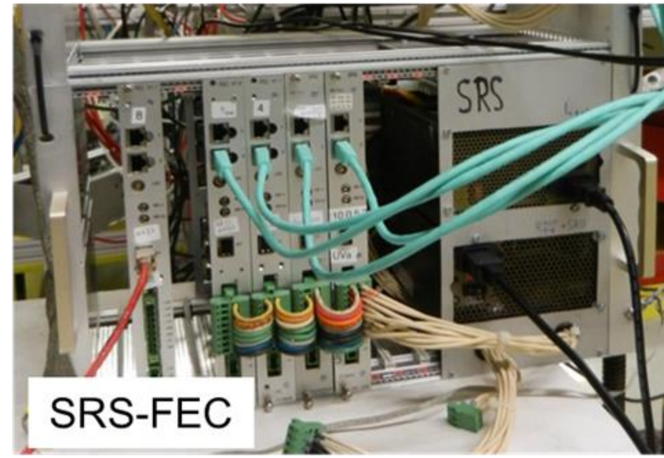


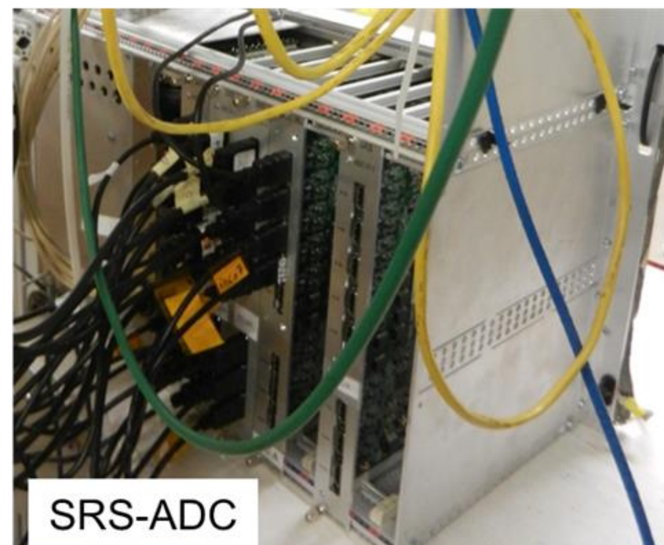
SRS readout for PRad GEMs

Need for PRad GEM chambers ⇨ (9216 e- channels)

- Experiment trigger peak rate at 5 kHz
- Each GEM chamber:
  - 3 (4) ADC/FECs (firmware upgrade) with 12 (9) APVs cards each with 3 time samples
  - 1 SRU collected the data to the DAQ PC through 10 Gb link (firmware upgrade)
- Integration of the SRS electronics into JLab DAQ (CODA software)







SRS readout: Challenges @ 5kHz trigger rate

- Data from APV25 data to FEC cards:
  - 3 time samples: readout mode is about 100 kHz (10 μs), no problem for PRad GEMs readout
- Data from FEC to SRU: 1Gb Ethernet cable (125 MB/s), data transfered through UDP
  - Rate capability limited 640 Mbps: 800 Mbps line speed (Why I don't know?) × 80% (for 8b10b line encoding overhead).
  - 3 time samples mode: the APV25 data size per event is ~ 1 kB ⇨ transfer rate @ 5 kHz = 5 MB/s
  - Fixed trigger rate: 12 APV25 per FEC/ADC, the data transfer is 60 MB/s and with 9 APV25 ⇨ 45 MB/s (safe mode)
  - Random trigger rate: situation is worse ⇨ Need firmware upgrade: Implementation of trigger buffering
- Data from SRU – DAQ PC: from 1 Gb to 10 Gb optical fiber
  - Default SRU implementation: 1 G Ethernet cable (125 MB/s), data transfered through UDP
  - First bottleneck to address: SRU data from 36 APV25 ⇨ minimal transfer rate @ 5 kHz = 180 MB/s
  - Firmware upgrade: Implementation of 10 Gb optical link to the DAQ PC
- Data from DAQ PC to the disk: Writing APV25 data (no zero suppression) into disk @ 5kHz is a challenge (~ 360 MB/s)
  - Need online zero suppression at the event building level on the DAQ PC
  - Event size to be reduced by more than a factor 100
  - Pedestal data and zero suppression algorithm is under development

Upgrade of SRU Firmware: Implementation of 10 Gb Optical link

(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

Existing SRU firmware from RD51 CERN

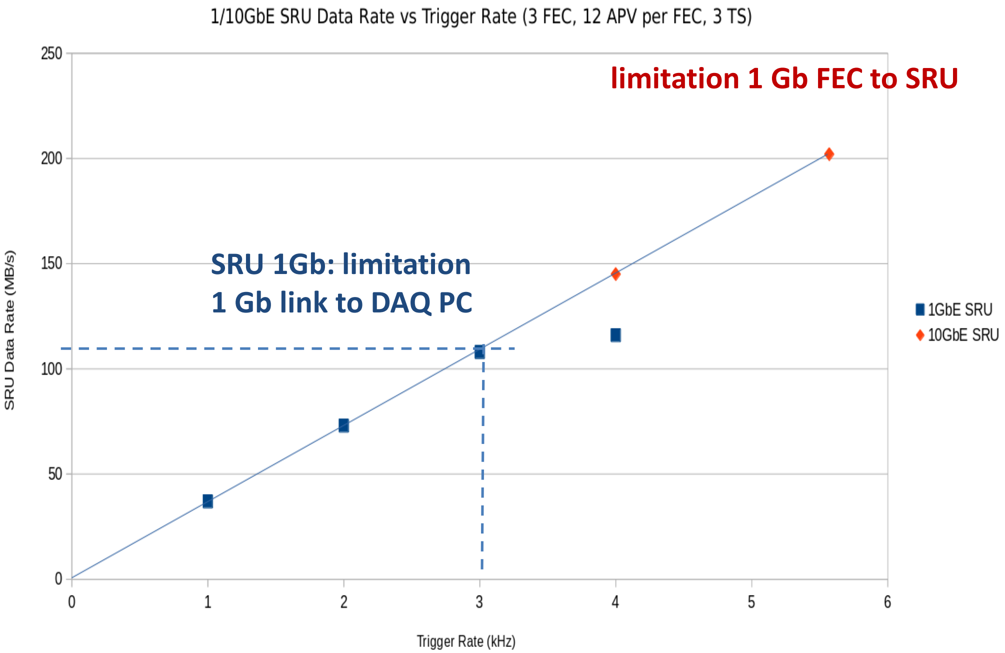
- Standard SRU firmware developped for the APV25 electronics with 1 Gb Ethernet link
- 10 Gb firmware was developped and tested in 2012 but was not compatible with standard SRU firmware

Upgrade of APV25-compatible 10 Gb SRU firmware (JLab DAQ)

- Merging the two firmware

Test Setup

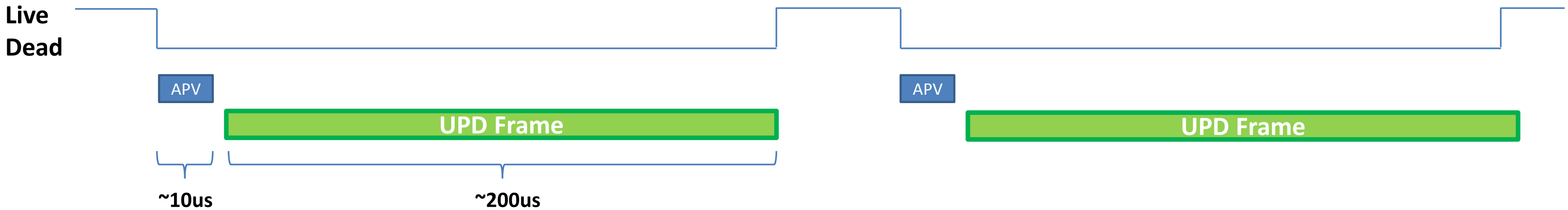
- 36 APVs, 3 Time sample, 3 FECs (Event size 38.5 kB)
- APV25 calibration pulse with internal trigger
- We tested the rate with standard 1(Gb) and upgraded (10 Gb) APV25-SRU firmware
- 1 Gb link (SRU): Saturation observed beyond ~3.2 kHz (Max. expected rate before saturation ~ 3.3 kHz)
- 10 Gb link (SRU): linear data transfet speed up to 5.5 kHz ⇨ saturation expected beyond 6 kHz (FEC data to SRU @ 80 MB/s)



Upgrade of FEC Firmware: Principle of Trigger Buffering

(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

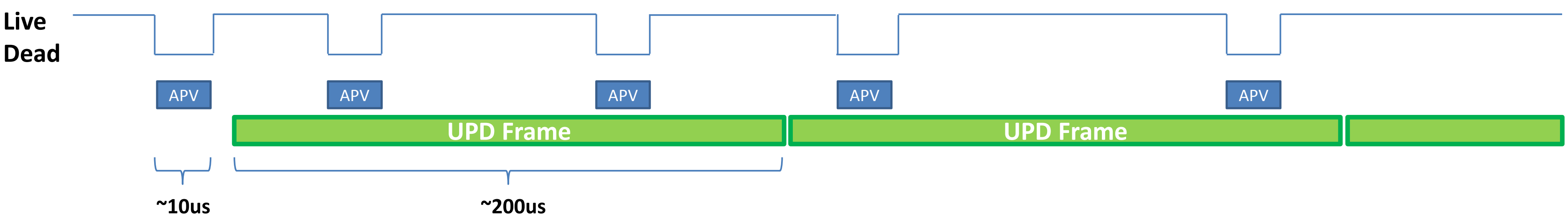
Non-buffered trigger FEC firmware (original):



- Dead/busy while APV sends triggered data **and dead/busy while UPD packets are sent**
- For fixed trigger rate, the dead time is basically determined by the UDP data processing (~200 μs)
- For random trigger: the mechanism is inefficient

  ⇨ no use of live time with low trigger burst but high trigger burst mean data loss because of dead time

Buffered trigger FEC firmware (new):



- Dead/busy while APV sends triggered data, **no longer dead/busy while UPD packets are sent**
- **UDP processing of APV data is “de-correlated” from APV sending data**
- When buffers in FPGA (holding captured APV for UDP processing) become full, then the FEC create necessary dead/busy time.
- For random trigger, @ high trigger burst, APV data are stocked in buffer and UDP packet is formed during the low trigger burst
- Dead/busy time while APV sends data can be eliminated to improve live time, but requires significant changes to FEC firmware.

Upgrade of FEC Firmware: Source codes changes

(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

Old firmware (standard)

- APV chip has a 4096 deep sample buffer. When capturing a few samples (e.g. 3), only a fraction of this buffer is used.
- The firmware performs the following steps sequentially:
    1. receive a trigger
    2. capture APV data
    3. wait for the data to be fully processed by the UDP processor
    4. Ready to accept another trigger.

New firmware

- writes multiple events in the existing buffer circularly. A new FIFO was added that gives a pointer into this buffer (along with other trigger header information) to the UPD packet processor.
- The new firmware performs the following steps in parallel:
    1. Receive a trigger, capture APV data, ready to accept another trigger
    2. Check trigger FIFO, build UPD packets
    3. Check circular buffer and assert BUSY if no more events can be accepted.
- Trigger processing dead time ~25 microseconds with up to 10 triggers can be buffered
- BUSY output (NIM Out): Busy Feedback to Trigger Supervisor to allows for more efficient acceptance of triggers without assumptions of FEC processing dead time.
- Without buffering, as a test example, we needed up to 70kHz input rate to readout near 5kHz ⇨ dead-time close to 100%. With buffering enabled the input rate could be slightly over 5kHz to readout near 5kHz ⇨ dead-time just a few percent.

Upgrade of FEC Firmware: Preliminary Tests

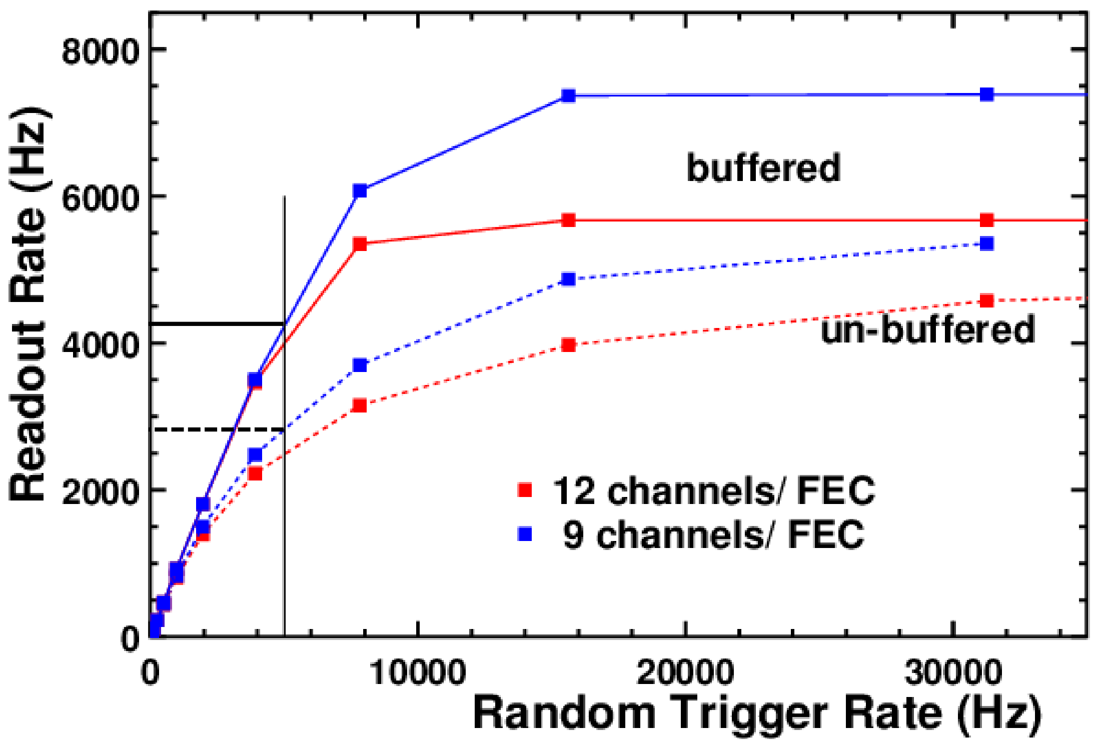
(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

Tests

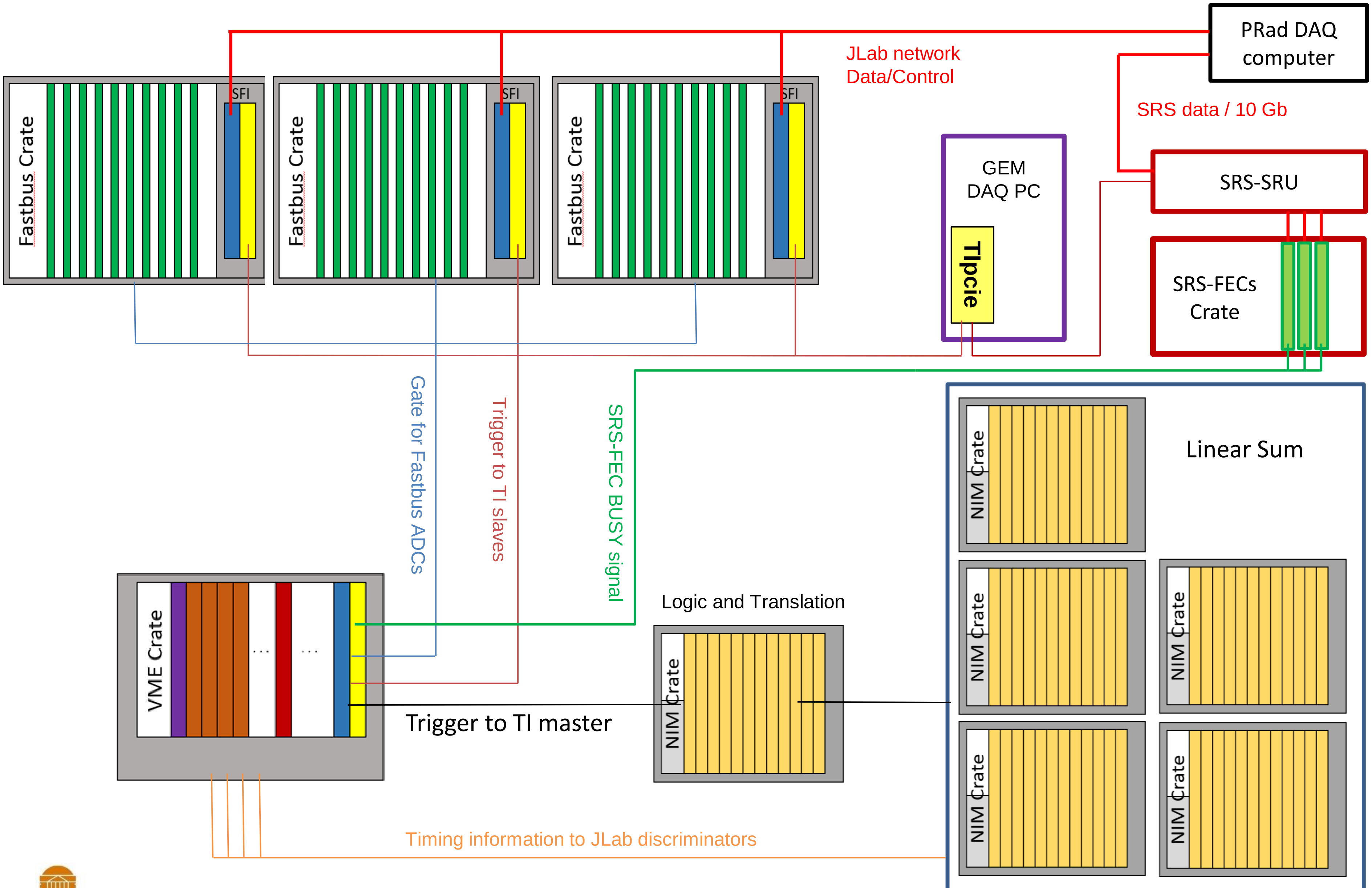
- 9 / 12 APV25 (ADC channels), on 1 FEC with 3 time samples to the SRU (Expected configuration for PRad)
- Random pulse generator board with both buffered and un-buffered Trigger tested simultaneously
- Ongoing tests with 4 FECs and 36 APVs

@ 5 kHz random trigger rate

- Un-buffered triggers firmware: readout rate of ~2.8 kHz (9 APVs on FEC) ⇨ 44% dead time
- Buffered trigger firmware: readout rate of ~4.25 kHz (9 APVs on FEC) ⇨ 15% dead time, OK for PRad



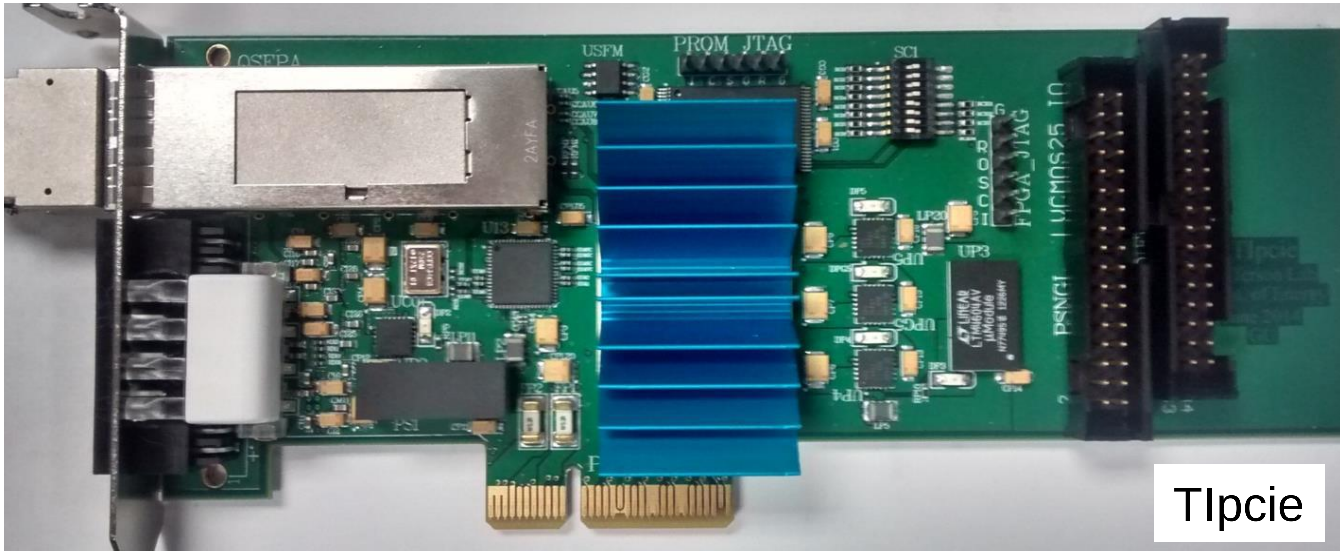
Integration of SRS into JLab DAQ: PRad DAQ Overview



Integration of SRS into JLab DAQ: Hardware

(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

- PCIexpress Trigger Interface (TIpcie)
  - PC / Server Integration into JLab Pipeline DAQ
  - Allows for using multiple cores/threads for data processing / data reduction
  - Standard PC Hardware allows for multiple network cards (1G, 10G, Infiniband)
  - Fiber Connection (Clock, Trigger, Sync) to Trigger Supervisor
  - Runs in Standalone (Master) or Larger-Scale DAQ (Slave).
  - Kernel and userspace driver compatible with EL5, EL6 (i386, x86_64)
- Interface to the SRS
  - SRU receive the trigger from the TIpcie
  - FECs send BUSY signal to Trigger Supervisor either directly or via the TIpcie



Integration of SRS into JLab DAQ: Software development

(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

Software librairies for the slow control

- C Library written to be used with CODA, **but also works standalone**
- Compatibility: REDHAT EL5, EL6 (i386, x86_64)
- Uses calls to routines for the configuration and readout
  - instead of using system calls to external programs/scripts
  - Still has the capability of reading in the original configuration text files.
  - More ‘human’ readable, Parameters can be input in any base (hexadecimal, decimal)
- Allows for iterating over several FEC with similar configuration

Online monitoring

- Before zero suppression (not implemented at the firmware level)
  - Raw APV data frames are available for online monitoring during the life time of PRad run
  - Monitoring of the all APV25 FE proper initalisation after DAQ reboot
- Zero suppression at software level during Event Building stage in the DAQ PC
  - Online monitoring of hits in the chamber and hits information
  - Clusterization algorithm for real time characterisation of the GEM chambers
  - 2D hit map, Gain uniformity, ADC distribution etc ...
  - Hits and cluster informations passed to the event data file to be written into disk

PRad Collaboration Institutional List

Currently 16 collaborating universities and institutions

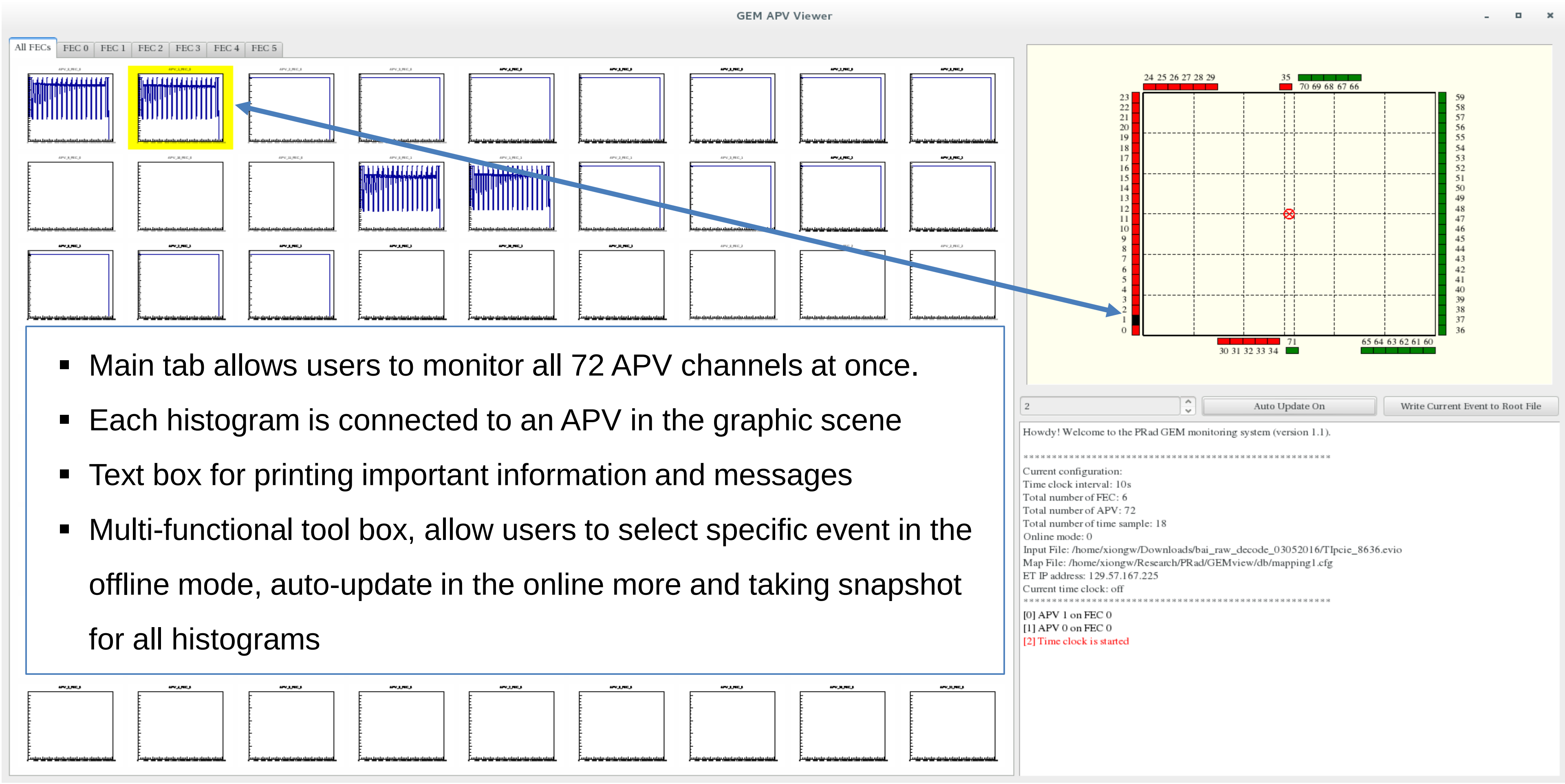
- Jefferson Laboratory
- NC A&T State University
- Duke University
- Idaho State University
- Mississippi State University
- Norfolk State University
- University of Virginia
- Argonne National Laboratory
- University of North Carolina at Wilmington
- University of Kentucky
- Hampton University
- College of William & Mary
- Tsinghua University, China
- Old Dominion University
- ITEP, Moscow, Russia
- Budker Institute of Nuclear Physics , Novosibirsk, Russia

Summary

- APV25-based SRS is the readout electronics for the Prad GEMs
    - Readout System is based on the standard SRS with the ADC/FEC/SRU board
    - 9216 electronic channels to be read out at 5 khz peak rate
- Firmware upgrade to allow high rate capability
    - SRU firmware: implementation of 10 Gb optical link for the data transfer from the SRU to the DAQ PC
    - FEC firmware: Implementation of the buffering trigger ⇨ allow 5 kHz trigger rate with limited dead time
- Integration of the SRS into JLab DAQ system
    - JLab custom board TIpcie for the trigger interface between SRS and Prad DAQ system
    - Development of the TIpcie libraries and slow control routines
    - Development of the online monitoring software
- Successfull preliminary tests of the new development
    - Test of the buffering trigger shows live time improvement from 56% to 85% at 5kHz trigger rate
    - Integration into JLab DAQ and interface with the TIpcie also successfulli tested
    - Data decoder software also have been tested and online software zero suppression is under development

Back Up

Online Monitoring for PRad GEM & Electronics



- Main tab allows users to monitor all 72 APV channels at once.
- Each histogram is connected to an APV in the graphic scene
- Text box for printing important information and messages
- Multi-functional tool box, allow users to select specific event in the offline mode, auto-update in the online more and taking snapshot for all histograms